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ACTIVATION OF SWEEPING MAGNETS IN TEVATRON II "STANDARDIZED" TARGET PILES

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1. Introduction

As designs of the primary targeting schemes for the new Tevatron II slow spill beams progress, it is becoming clear that a standardized form for these schemes is emerging. The general form consists of a production target (usually about 30 cm of beryllium having a diameter from 0.64 to 1.27 cm) followed by from one to three of the new Tevatron II "H" frame magnets recently developed by D. Eartly. These magnets sweep the unused primary proton beam onto a massive steel beam dump containing a core of material capable of dispersing the energy of the beam along with a hole for transmitting the secondary beam desired at experimental targets. Typical primary proton intensities at such production targets are planned to be in the range of 3×10^{12} to 5×10^{12} protons per spill. If one assumes such operation during a run of 4000 hours per year, 60 spills per hour, the integrated beam is seen to be approximately 1×10^{18} per year targetted at a rate of $7/0 \times 10^{10}$ protons/sec during the run.

It is clear, from experience, that such beam intensities require that the water be used to cool the beam dump must be in a closed loop system both to protect personnel during operations from the external radiation exposure rate due to short lived radionuclides (e.g., ^{11}C and ^{7}Be) and to protect against release of significant activities of tritium into surface waters. It is not certain that a closed loop system is required for the sweeping magnets. This TM reports on a calculation designed to evaluate this potential problem, the expected dose rates external to such magnets, and the total activity which will be contained in them and the target.

2. Monte-Carlo Calculations

The Monte-Carlo hadronic cascade code CASIM written by A Van Ginneken[1] (FORTRAN 5 Version) was used to model the geometry. Figure 1 shows a cross-sectional view of the sweeping magnets as designed including a detailed cross section of the coils. Figure 2 shows how this magnet cross section was approximated in the calculation. In the calculation, a 30cm long beryllium target of a specified radius was placed immediately upstream of a string of three of these magnets. Each magnet is 12.5 ft (381 cm) long. The three magnets were, for simplicity treated as one continuous magnet. The coils were modeled to be solid copper but with a density of 8.3 g/cm^3 used to take into account the presence of the cooling water.

The primary proton beam was brought "straight ahead" into the target with a momentum of 1000 GeV/c in a parallel and horizontally and vertically symmetric Gaussian profile having a value of σ = 1mm. A magnetic field of 18 kG was used in some of the calculations and turned off in others to test its effect upon the results. Two different random number seeds were used in the calculations and 10000 incident particles were followed in each case. In all of the calculations, the conventional star densities per incident proton were collected as a function of position in the material while an integration to obtain the total stars per incident proton in each different material (beryllium, copper, and steel) was performed. The integral values were used to calculate activities while the star densities were used to calculate expected external dose rates. The threshold for the calculation was 0.3 GeV/c corresponding to a nucleon kinetic energy of 47 MeV.

One calculation was made to estimate the consequences of a missteered primary beam hitting the magnets instead of the target. It is clear that the rapid buildup of the hadronic cascade in these magnets would cause activation problems far in excess of the results given below.

3. Activation of Cooling Water

This activation is best calculated by following the procedures of an early TM written by M. Awschalom - TM408A[2] where a similar calculation was reported. Table 1 shows the number of stars per proton produced in the coils for the several operating conditions. As one can see, the results are not strongly dependent upon either target radius or magnetic field strength. Dependence upon random number seed is also weak indicating good statistics are present in the calculations. A value of 30 stars/proton would seem to be reasonable. In the present geometry, 8.7 per cent of the volume of the coils are occupied by water. At this point in the calculation it is necessary to relate the number of stars in the water itself to the total number of stars in the coils. Following the method of Reference 2, we obtain total nonelastic cross sections interpolated from Belletini[3] and from the Particle Data Group[4]. For consistency, values at 20 GeV were used:

σ_{ne} (H)	30 mb	Ref. 4
σ_{ne} (O)	310 mb	Ref. 3
σ_{ne} (H_2O)	370 mb	--
σ_{ne} (Cu)	850 mb	Ref. 3

converting these to macroscopic cross sections Σ:

$$\Sigma = \frac{\rho N \sigma}{A}$$

with N = Avogradro's number, ρ = the density, and A = the molecular weight we obtain

$$\Sigma(Cu) = \frac{8.96 \times 6.02 \times 10^{23} \times 0.850 \times 10^{-24}}{63.54} = 7.22 \times 10^{-2}\,\text{cm}^{-1}$$

$$\Sigma(H_2O) \quad \frac{1.0 \times 6.02 \times 10^{23} \times 0.370 \times 10^{-24}}{18.00} = 1.2 \times 10^{-2}\,\text{cm}^{-1}$$

It is this obvious that the ratio of nuclear stars in water to total stars in the coils is given by:

$$\frac{\text{water stars}}{\text{all stars}} = \frac{0.087 \times 0.0124}{0.087 \times 0.0124 + 0.913 \times 0.072} = 0.016$$

At this point production cross sections are needed. The most complete summary is that of Barbier[5]. It is clear that spallation of oxygen is the most serious contributor to radionuclide production in water and Barbier's Figure IV-22 reproduced here as Figure 3 shows the relevant cross sections. From this figure we can obtain the following cross sections (taking conservative values) which are listed along with the half-life of the nuclide. It might be noted that, fortuitously, these nuclear reactions have thresholds crudely equal to the 47 MeV nuclear threshold of the present calculation.

Nuclide	σ(mb)	$t_{1/2}$ (half-life)
^{3}H	35	12.3 years
^{7}Be	10	53.3 days
^{11}C	10	20.4 minute
^{13}N	5	9.96 minute
^{15}O	30	2.03 minute

For the five nuclides of interest, we can now obtain the number of atoms produced per incident proton:

$$\frac{\text{nuclide atoms}}{\text{incident proton}} = \frac{\sigma(\text{nuclide})}{\sigma_{ne}\ (\text{water})} \times \frac{\text{water star}}{\text{all stars}} \times \frac{\text{all stars}}{\text{proton}}$$

These are tabulated below:

Nuclide	Nuclide atoms / Incident Proton
^{3}H	0.045
^{7}Be	0.013
^{11}C	0.013
^{13}N	0.006
^{15}O	0.039

The four short-lived radionuclides will easily reach equilibrium concentrations during a typical Tevatron II run of several months such that the rate of decay will equal the rate of production.

Recognizing that the three magnet system studied here contains 28900 cm^3 of water, (7.6 U.S. gallons) at equilibrium, converting to units of $\mu Ci/cm^3$ (1 Curie = 3.7×10^{10} nuclear disintegrations/sec) at the proton targeting rate stated above ($7 \times 10^{10}\ sec^{-1}$) we will obtain concentrations for the water in the coils alone and for its dilution in a 100 gallon gallon system:

Nuclide	Concentration ($\mu Ci/cm^3$) (coils alone)	100 Gal. system
^{7}Be	0.85	0.065
^{11}C	0.85	0.065
^{13}N	0.39	0.030
^{15}O	2.55	0.194

The short half-lives involved make these concentrations only a possible problem of personnel exposure principally due to ^{7}Be collected in the deionization bottles and to ^{11}C in the water. ^{11}C

is obviously only a possible problem for the first hour or so after the beam is turned off.

At the end of a run essentially all of the ^7Be would be trapped in the deionization bottles. This would amount to about 25 mCi. ^7Be decays to ^7Li 89.7 per cent of the time to the ground state and 10.3 per cent of the time by emitting a 477 keV gamma ray. A well-known formula[6] relates the exposure rate due to a point source to the activity and the energy of the emitted gamma rays:

$$D = 0.48 \, \Sigma \, f_i \, E_i$$

D is the exposure rate in R/hr per Curie of activity while the summation is over all gamma rays emitted with energy E_i (MeV) and branching fractions f_i.

If all the equilibrium ^7Be is concentrated at one point we have:

$$D(^7Be) = 0.48(0.103)(0.477)(0.025 \text{ Ci}) = 0.0006 \text{ R/hr}$$

$$= 0.6 \text{ mR/hr at one meter}$$

and is thus only of slight importance if access to the bottles is restricted. Of course the resin in the bottles would be contaminated. Likewise, if all the ^{11}C in equilibrium were to be concentrated at the bottles, taking into account that ^{11}C is a positron emitter thus producing two 511 keV annihilation gamma rays per decay one would have:

$$D(^{11}C) = 0.48(2)(0.511)(0.025 \text{ Ci}) = 0.012 \text{ R/hr}$$

$$= 12 \text{ mR/hr at one meter at time of beam shut-off.}$$

Thus these radionuclides lead to only minor exposure problems due to the water cooling these sweeping magnets if some decay time for ^{11}C is allowed. The deionization bottles must be located in areas of minimum occupancy, preferably inside of a shielded area.

Now we come to tritium (^3H) where we have a prediction of 0.045 atoms per incident proton. The buildup to equilibrium is too slow to be a practical consideration so instead consider the concentration after one year's targeting of 10^{18} protons. This would result in a concentration in the coils of alone of

$$C(\text{Coils}) = \frac{0.045 \text{ atoms}}{\text{proton}} \times \frac{10^{18} \text{protons}}{28900 \text{cm}^3} = 1.56 \times 10^{12} \frac{\text{atoms}}{\text{cm}^3}$$

and using the decay constant $\lambda = 1.79 \times 10^{-9} \text{ sec}^{-1}$

$$C \text{ (Coils)} = 75470 \text{ pCi/cm}^3$$

If this is diluted into a 100 gallon ($3.79 \times 10^5 cm^3$) C = 5755 pCi/cm^3. If this were not be a closed loop system a volume of at least 600 gallons would be necessary to reduce the concentration to less than the D.O.E. concentration limit of 1000 pCi/ml for such an open loop system. It must be remembered that if more than one target pile is sharing the LCW system, the concentrations will be determined by the sum of the tritium production rates. Also, if the same water is activated for more than one year these concentration will exponentially rise toward the equilibrium value of approximately 18 times larger. An important consequence of using open-loop LCW is the fact that measurable (but allowable) tritium concentration will be spread throughout the system into areas where they otherwise would not be found.

Of course, during operations it is not easy to preclude accidental targeting on the magnets. To test the affects of such beam tuning a separate CASIM run was made with the beam missing the target and hitting the pole piece of the first magnet with a Gaussian beam spot of σ = 1m hitting the magnet 1 mm inside the pole piece. In that calculation, with a magnetic field of 18 kG in the magnet gap, 90 stars per incident proton were produced in the coils. Thus the beam could hit the magnets for perhaps one-tenth of the time without the tritium concentration increasing by more than 30 per cent.

4. External Dose Rates

It is interesting to have an advance prediction of the external dose rates of such magnets. Figures 4 and 5 are contour plots of equal star densities as a function of depth and radius aximuthally averaged for magnetic field off and on, respectively. The dependence upon target radius is very weak and is not shown. Looking at the value of R representing the side of magnet closest to the beam (R = 27cm) we see a maximum star density of 3×10^{-5} $stars/cm^3$ per incident proton. The presence of the field serves to extend the region of this large a surface star density downstream by sweeping off momentum charged particles into the magnets. To calculate an estimate of the dose rate, the prescription of Gollon[7] will be followed by use of the formula,

$$D = \frac{\Omega}{4\pi} \; S \; w$$

where Ω = the solid angle subtended by the source, S = the average rate of star production per cm^3 (stars $cm^{-3} sec^{-1}$) and w is a function of the irradiation time, and the cooldown time. Usually, the values of w are taken to be:

$$w(\infty,o) = 9.0 \times 10^{-6} \text{ rad hr}^{-1}/(\text{star/cm}^{-3}\text{ sec}^{-1})$$

$$w(30d,\ 1d) = 2.5 \times 10^{-6} \text{ rad hr}^{-1}/(\text{star/cm}^{-3}\text{ sec}^{-1})$$

A magnet about 1 ft away would subtend about π steradians at most. Assuming an intermediate length run with an intermediate cool down period implying $w = 6 \times 10^{-6}$, we have:

$$D = \frac{\pi}{4\pi} \; 3 \times 10^{-5} \; \frac{\text{stars}}{\text{cm}^3} \times 7 \times 10^{10} \; \frac{\text{protons}}{\text{sec}} \times 6 \times 10^{-6} \frac{\text{rad hr}^{-1}}{\text{stars cm}^{-3}\text{sec}^{-1}} = 3.2 \text{ rad/hr}$$

which agrees well with other Fermilab experience. It should be clear from Figure 4 and 5 that the front face of the first magnet in such a string may be as much as 10 to 100 times hotter in small area near the target.

Figure 6 shows the same contour plot for the case of the magnet being directly hit. In this figure we see that the upstream magnets are more radioactive by about a factor of 10 since we now have a massive target (the magnets) in the primary beam. It is obvious that such accidental targeting needs to be prevented as much as possible so as not to create a severe exposure rate problem during servicing operations.

4. Total Activity of the Magnets

At time of disposal it is useful to know both the total activity and the specific activity of the steel. The present calculation also yields values for total number of stars in the steel which are shown in Table 2, where it is clear that a value of 170 stars/proton is reasonable. Experience has shown ^{54}Mn ($t_{1/2}$ = 312 days) to be the most prolifically produced radionuclide. If one assumes a production cross section of 10mb for this isotope and compares this with a value of $\sigma_{ne} = 760$ mb for iron interpolated from Reference 3 one sees that 10/760 of all stars produce a ^{54}Mn atom. Since the lifetime of such a target scheme exceeds (hopefully!) several half lives, one can go directly to the equilibrium production rate (now averaged over the one year cycle) and obtain

$$\frac{0.013 \; ^{54}\text{Mn atoms}}{\text{star}} \times \frac{170 \text{ stars}}{\text{proton}} \times 3.2 \times 10^{10} \frac{\text{protons}}{\text{sec}}$$

$$= \frac{7.07 \times 10^{10} \; ^{54}\text{Mn atoms}}{\text{sec}} = 1.9 \text{ Curies}$$

or roughly $0.64 \frac{\text{Curie}}{\text{magnet}}$ for the three magnet system.

Each magnet is about 14 U.S. Tons = 1.27×10^7 grams, so that the equilibrium specific activity = 50 nCi/gram or 394 pCi/cm^3.

The calculation done for the case of directly hitting the magnet gave a result of 600 stars/protons produced in the magnets. Figure 6 indicates that most of the corresponding additional activity would be produced in the first of the three magnets.

5. Activation of the Target

The calculation (quite reasonably) revealed that an average of 0.9 star per incident proton would be produced in the one interaction length beryllium target. This was approximately independent of target radius. Reference 3 gives a value of $\sigma_{ne} =$ 227 mb for 9Be at 20 GeV. The only radionuclide produced in the target sufficiently long-lived to present external exposure problems is ^{7}Be. E. Bruninx reports a reasonable value of $\sigma =$ 15 mb at a bombarding energy of 5.7 GeV for the ^{9}Be(p,x) ^{7}Be reaction. Taking a reasonable value of 20 mb at higher energies one obtains for the equilibrium production rate during a run:

$$\frac{\text{nuclide atoms}}{\text{sec}} = \frac{20\text{mb}}{227\text{mb}} \times \frac{0.9 \text{ stars}}{\text{proton}} \times 7 \times 10^{10} \frac{\text{protons}}{\text{sec}} = 5.6 \times 10^{9} \frac{\text{atoms}}{\text{sec}}$$

which in equilibrium amounts to 0.15 Ci of activity. All distances larger than 30 cm, this target can be represented as a point source. Following the methodology used above, at one meter away the dose rate will be:

$$D = 0.48(0.103)(0.477)(0.15) = 0.0035 \text{ R/hr}$$

$$= 3.5 \text{ mR/hr}$$

which compares well with 400 GeV results taking into account the reduced number of protons to be targeted per unit time in the Tevatron era.

6. Conclusions

It appears that an open loop (LCW) water system of around 600 gallons size can be used for such magnets if suitable precautions are taken to prevent excessive targeting on the magnets themselves. The deionization bottles will present nuisance levels of radiation and will be contaminated. Also, measurable tritium concentrations will be found throughout the system and a program of routine monitoring will be required.

The external dose rates at the side of the magnets, will be several rads/hr and thus can only be serviced under the constant supervision of radiation safety personnel. Estimates have been made of the total activities of these magnets.

I would like to thank D. Eartly for suggesting the problem studied here and A. Elwyn for reading the manuscript and making very helpful comments.

References

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5. M. Barbier, Induced Radioactivity (North Holland, Amsterdam, 1969) p. 189.

6. H. Cember, Introduction to Health Physics (Pergamon, New York, 1969) p. 164

7. P.J. Gollon, "Production of Radioactivity by Particle Accelerators", IEEE Trans. Nucl. Sci, NS-23 (1976) 1395.

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Table 1

Total Stars produced in copper coils per proton for different target Radii R

	Seed 1	Seed 2
1. Magnetic field on		
R = 0.64 cm	28.6	29.1
R = 1.27 cm	30.2	31.3
2. Magnetic field off		
R = 0.64 cm	24.3	25.5
R = 1.27 cm	25.5	24.5

Table 2

Total stars/proton in steel (3 Magnets)

	Seed 1	Seed 2
1. Magnetic Field on		
R = 0.64 cm	175	166
R = 1.27 cm	173	169
2. Magnets Field off		
R = 0.64	153	159
R = 1.27 cm	160	170

List of Figure Captions

1. Cross section view of a Tevatron II Target "H" Frame Magnet.

2. Cross section view of magnets as modeled in this calculation.

3. Production cross sections of protons on ^{16}O for various radionuclides copied from Reference 5.

4. Contours of equal star density in units of stars cm^{-3} per proton as a function of depth(Z) and radius (R) asimuthally averaged. The magnetic field is off.

5. Same as Figure 4 only with the magnetic field turned on.

6. Same as Figure 5 but with the beam missing the target and hitting the first magnet.

DC:mnm
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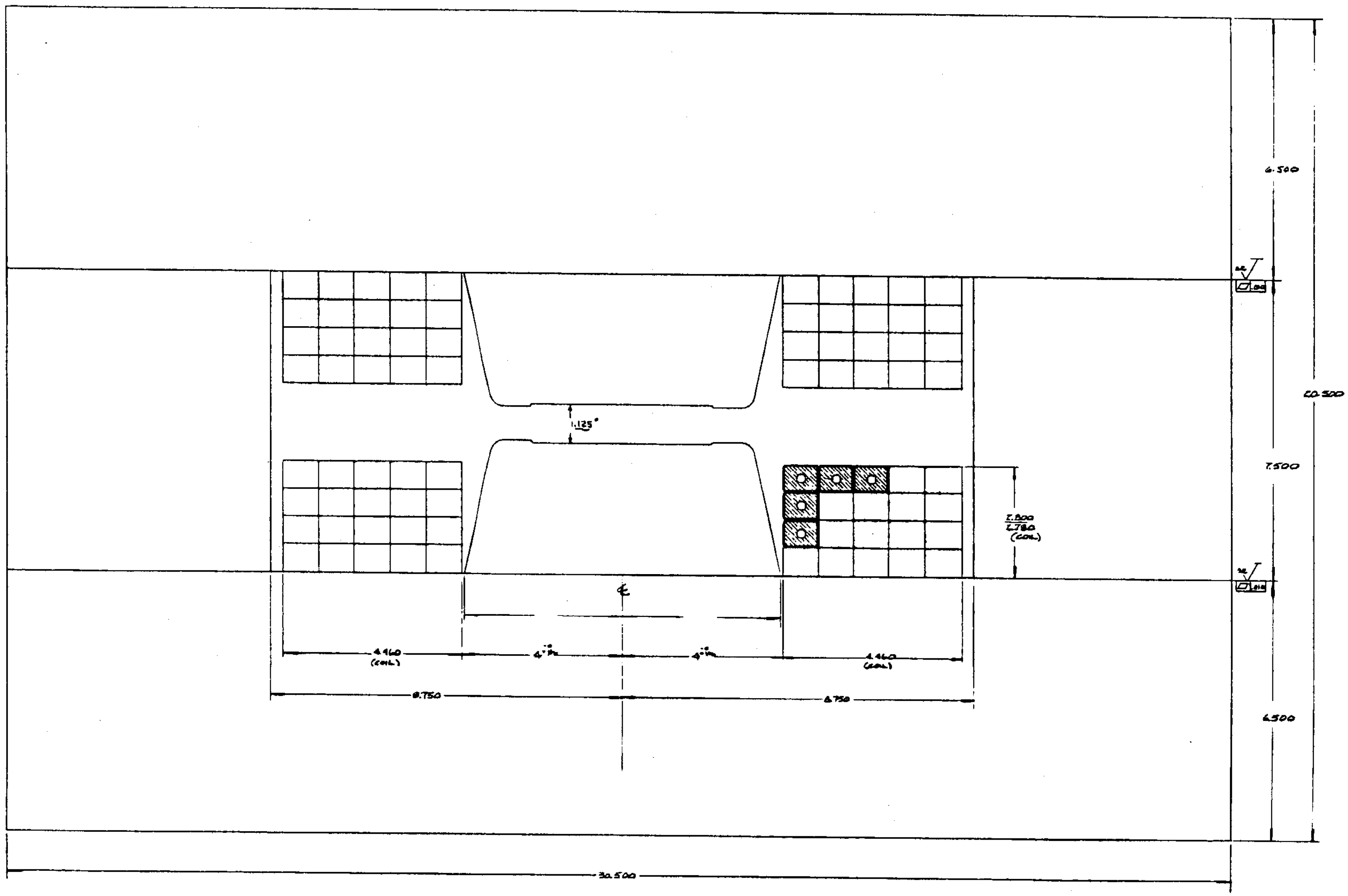

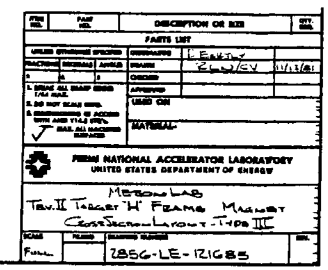

Figure 1 Cross Section of a Tevatron II Target "H" Frame Magnet

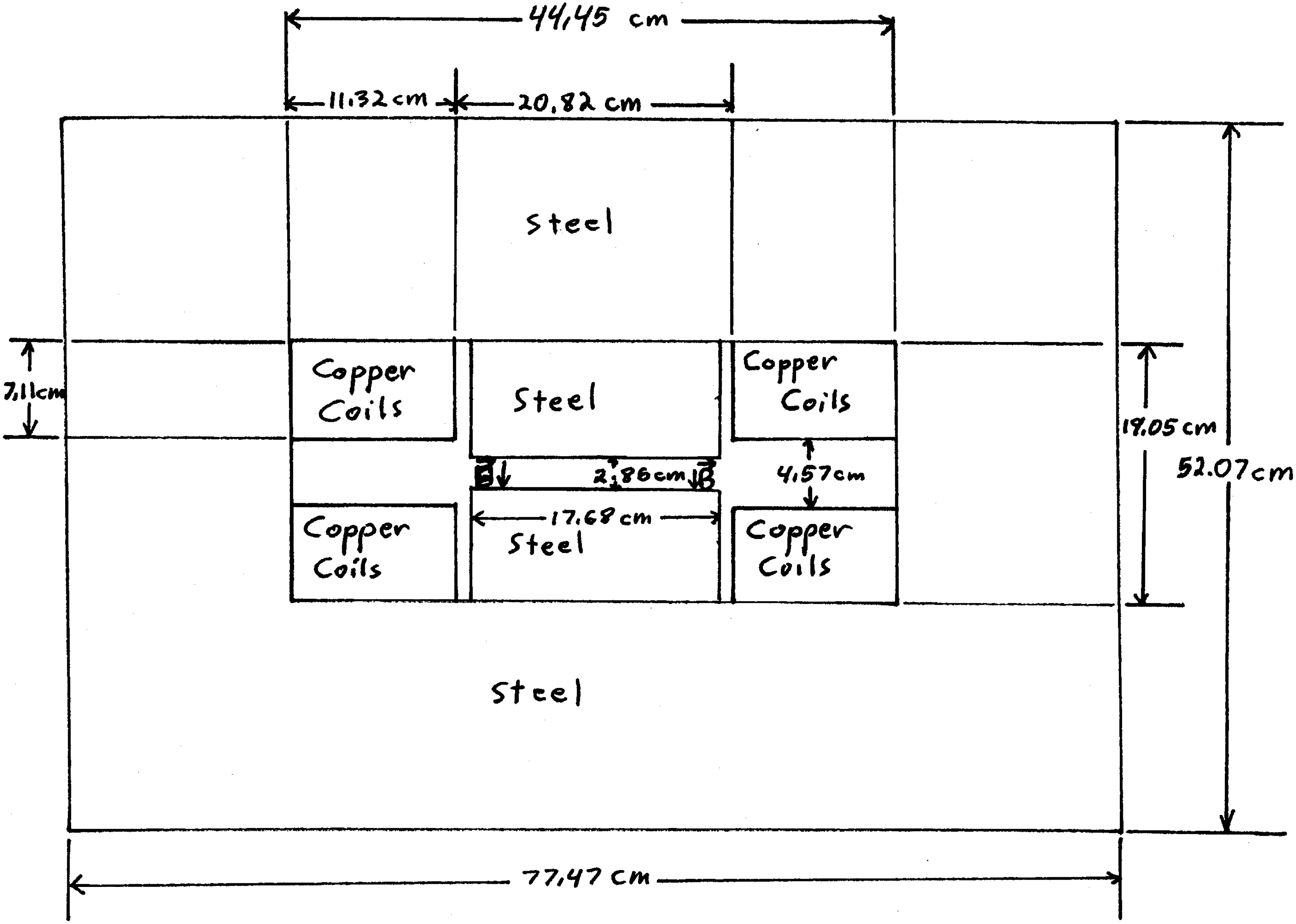

Figure 2 Cross Section View of Magnet as Modeled in This Calculation. $\vec{B}$ indicates the magnetic field region

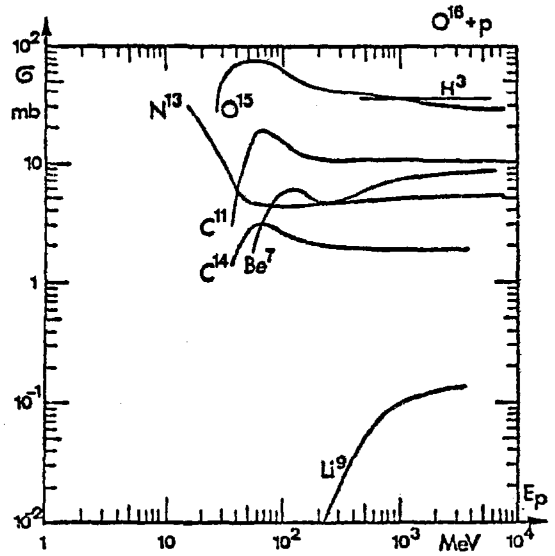

Fig. IV.22 Production cross-section of various isotopes in oxygen by proton bombardment.

Figure 3 Production Cross Sections of Protons on ^{16}O for Various Radionuclides Copied from Ref. 5

Figure 4 Contours of equal star density in units of stars cm^{-3} per incident proton as a function of depth (z) and radius (R) azimuthally averaged (field in magnet = 0)

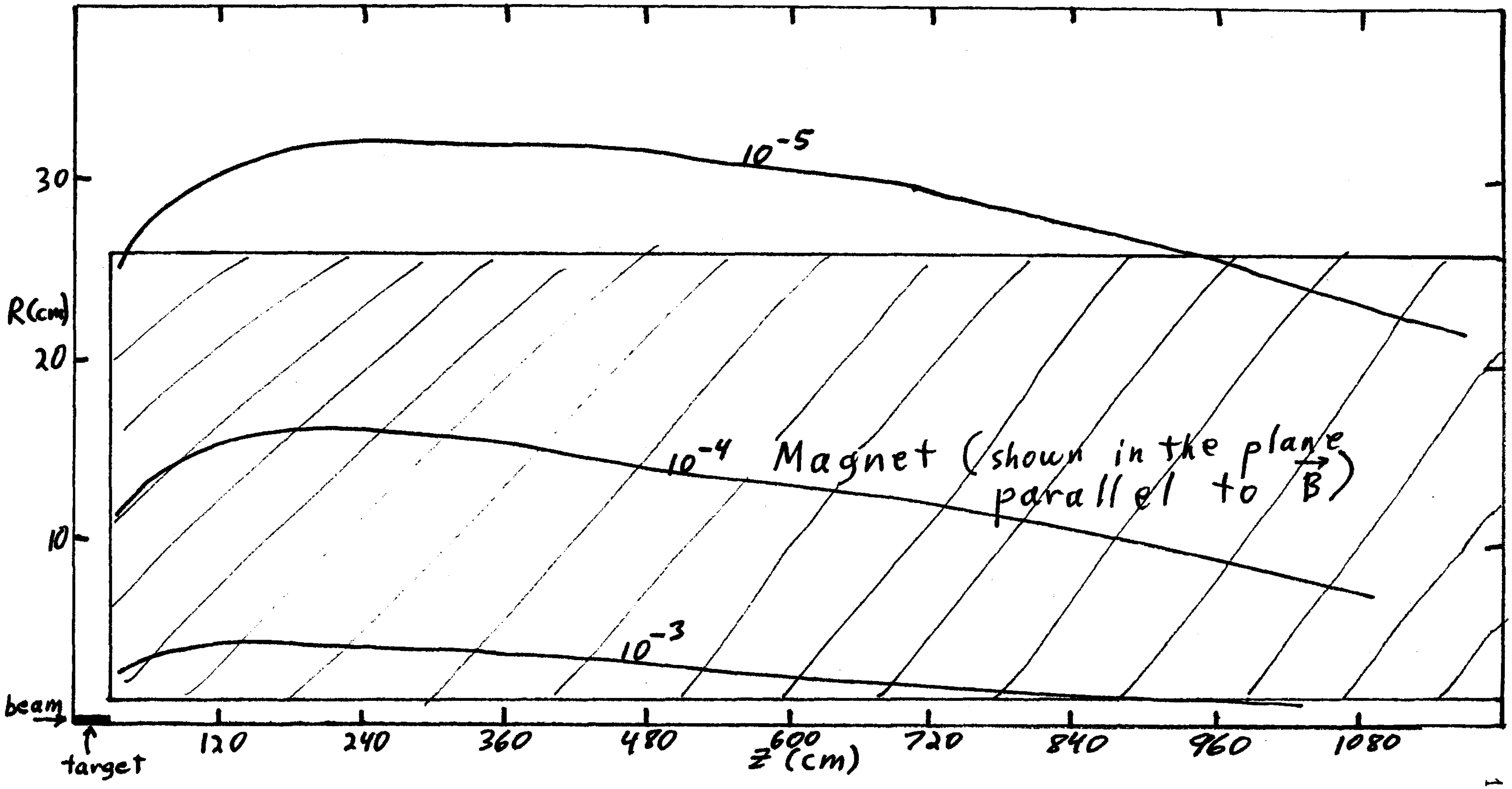

Figure 5 Same as Fig. 4 only the field in magnet = 18 kG

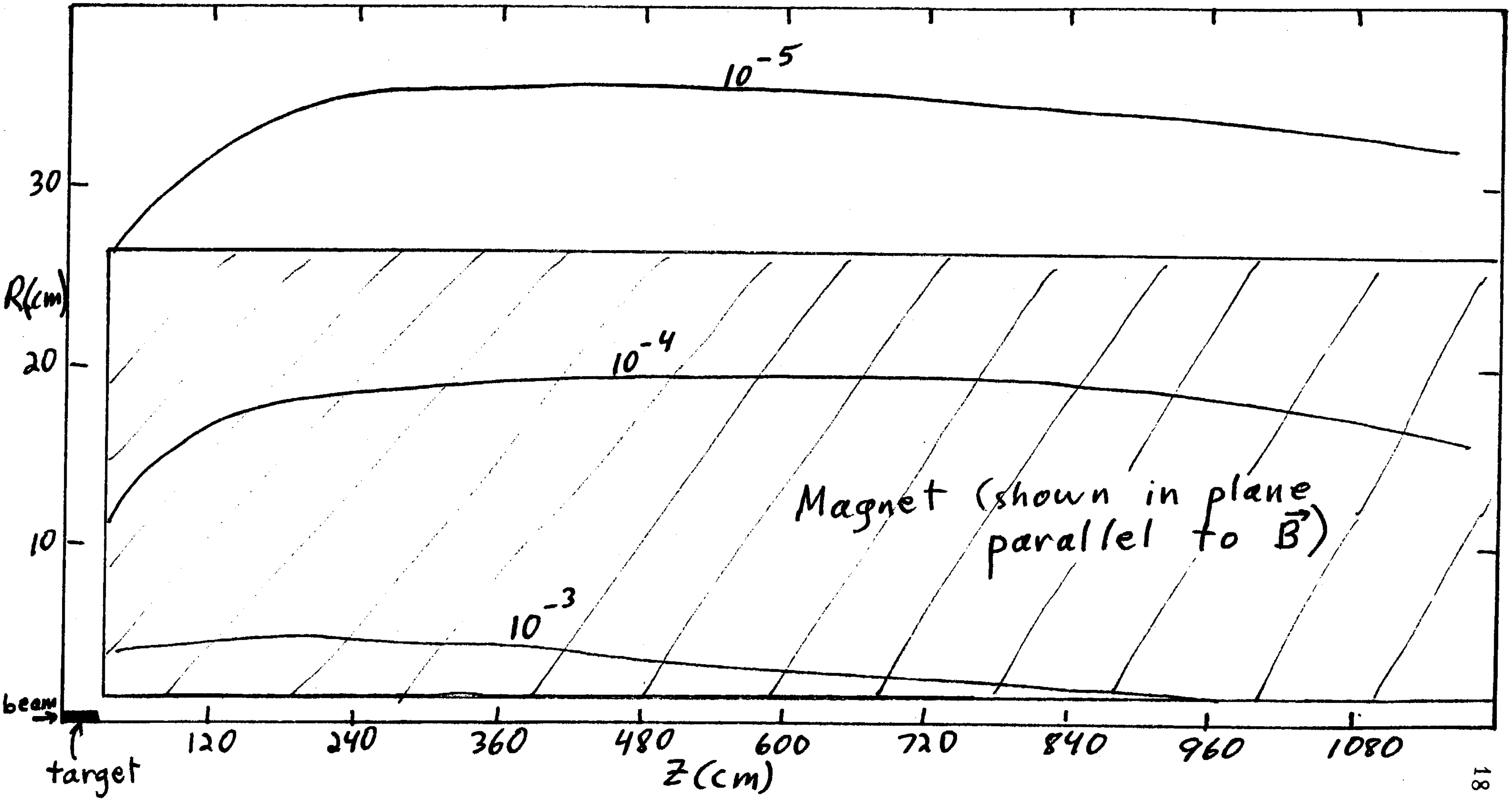

Figure 6 Same as Fig. 5 only with the beam missing the target and hitting the first magnet